6. ORBITAL COLLISION HAZARDS

6.1 ORBITING SPACE OBJECTS

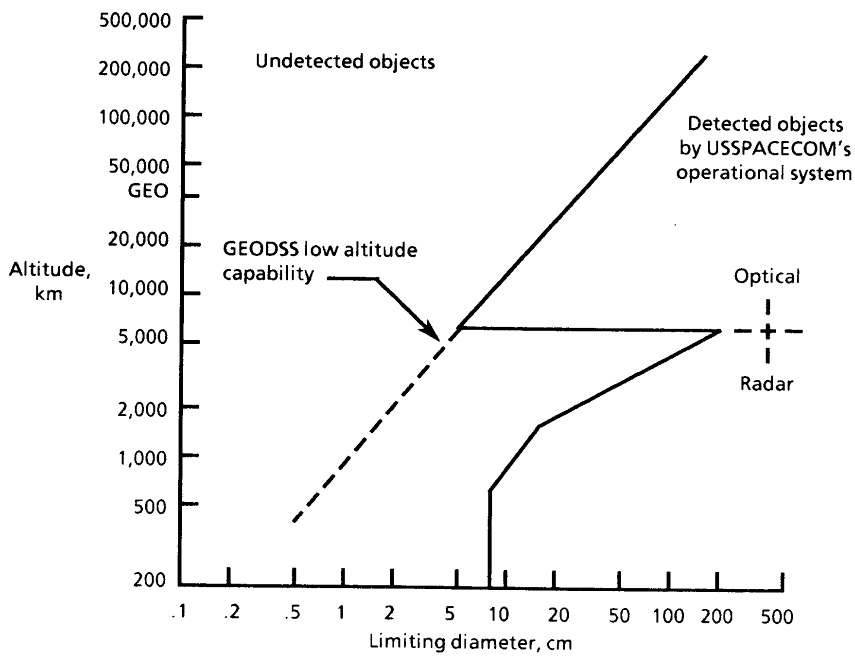
It is important to estimate the hazards of on-orbit collisions between space objects because the US may be liable for any damage to a foreign country, or satellite caused by a US spacecraft. The latest NASA Satellite Situation Report lists 1,702 spacecraft in orbit and 5,130 large debris such as spent rocket stages and payload shrouds.[4] Expanding the count to include trackable debris, the tally was 18,145 cataloged space objects as of June 30, 1987. Of these, 5,763 are from the US and 11,603 from the USSR. Of the total, approximately 7,000 are still in orbit (the rest have decayed and re-entered). Radar-trackable objects in space (i.e., larger than about 10 cm across) are monitored and cataloged by both the US Space Command (USSPACECOM). Considerably more objects and debris too small to be trackable are in orbit, as indicated in Figure 6-1.[1] Measurements using the USSPACECOM's Perimeter Acquisition Radar Attack Characterization System (PARCS), which is sensitive to objects of about 1 cm in size, yields the debris population shown in Figures 6-2 and 6-3. The tracked population has increased steadily since the early 1970's, as shown by a comparison of the number of cataloged space objects between 1976 and 1986.

During this period the tracked population has increased from 4100 to 4700 objects, compared with an increase of 25 percent in launch activity over the same period. This reflects the dynamic nature existing between new and decaying objects in space. (see Ch.7)

The 1986 Satellite Catalog (SATCAT) listed 16,660 entries, including all satellites launched in the last 30 years, their stages and trackable debris. However, only about 6000 of these objects are still in orbit, and about 44 percent of them originated from major on-orbit break ups (see Sec. 6.3.2).[4b, c]

Satellites are currently being launched into space at a rate of approximately 150-200 per year.[5] Eight countries presently possess space launch capability and over 100 nation-states participate in international satellite communication programs.[5-6] The rate of new objects cataloged is higher than the number of payloads because it includes debris. There were 983, 843 and 458 new objects cataloged during 1985, 1986 and 1987, respectively.

More than 3,600 payloads have been launched into space since 1957, but only 342 satellites were operational as of Sept., 1987, of which US operates 133, the USSR 148 and 13 other countries and international organizations, 61. Nearly half of this total are



Source; D. J. Kessler presentation to USAF, Jan. 1987 (Ref. 1)

FIGURE 6-1. GEODSS CAPABILITY TO DETECT OBJECTS AT LOWER ALTITUDES

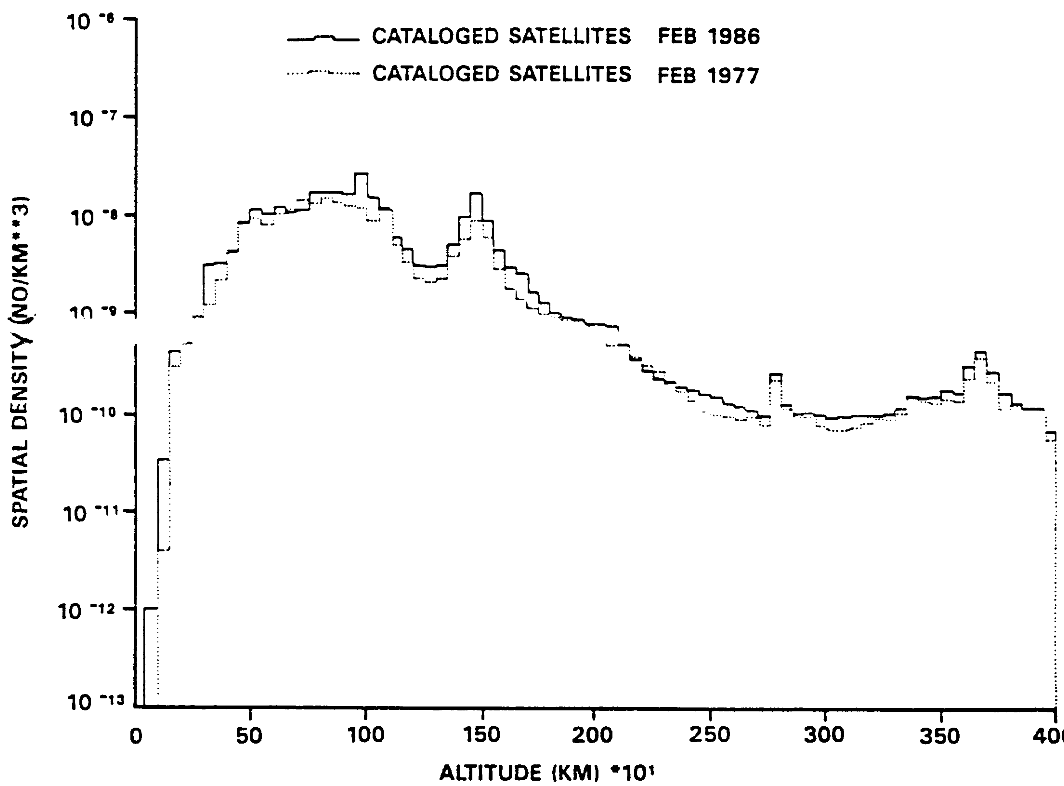


FIGURE 6-2. SPATIAL DENSITY OF SPACE OBJECTS VS. ALTITUDE (REF. 2)

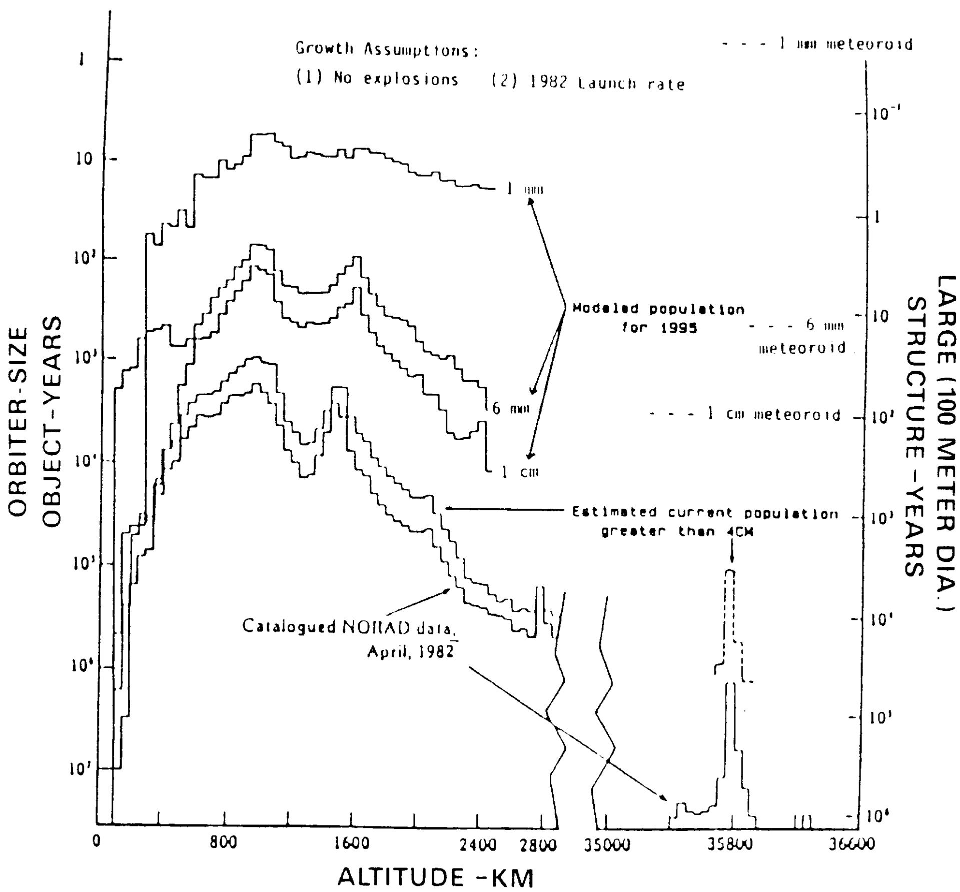


FIGURE 6-3. AVERAGE TIME BETWEEN COLLISIONS, MODELED POPULATION FOR 1995

military satellites. By aggregate satellite mass, the Soviets account for 2/3 of the total.[4b, 33] The total mass now in Earth orbit exceeds 500 tons; each year about 800 additional tons are launched.[2] Active payloads comprise only 5 percent of all objects in space. The other 95 percent, including dead payloads, expendable launch stages and debris fragments are also monitored in case they pose re-entry hazards (Ch. 7). The mass/number balance of space objects decaying and re-entering Earth's atmosphere vs. those in long lived "deep space" orbits (periods longer than 225 min) and the projected annual influx of decaying space objects will also be discussed in Chapter 7.[2]

The orbital collision hazards are under active consideration by several national agencies (NASA, DOD, DOS, DOT, DOC) and international organizations.

The "Unispace 82" conference acknowledged the growing threat to space activities posed by accidental collisions in orbit. The magnitude of the current and projected collision hazards for low-Earth orbit (LEO) and geosynchronous orbits (GEO) is shown in Figures 6-2 and 6-3.[1-3]

Several international agreements have been proposed, and are being considered to govern the orbital operation of satellites, disposal of inactive spacecraft and management of space debris. These agreements are limited primarily to the control of commercial communications satellites in geostationary orbits (GEO). Such agreements are motivated primarily by the need to prevent radio frequency interference between neighboring satellites, rather than to insure that collisions between satellites will not occur, given their relatively low spatial density. Depending on their orbital altitude and other parameters (inclination, eccentricity), mean orbital collision times for satellites range from a few years to as long as 1000 years. However, since the population of space objects is increasing rapidly in LEO and GEO orbits of interest, and since on-orbit debris increase even more rapidly, crisis proportions could be reached after the year 2000 unless debris management policies and procedures are adopted soon. Already, in 1979, the Japanese satellite ECS-1 was lost by a collision in space with the third stage of its own launch vehicle, causing a multimillion dollar loss.

Recent measurements and observations of satellite debris have indicated that the untracked man-made debris population in near-Earth and deep space orbits (of 1cm sizes in near-Earth and up to 20 cm in deep-space and GEO orbits) far exceeds the number of USSPACECOM-tracked fragments. These would augment the near-Earth amount of tracked debris by a factor of 10 and the debris orbiting in deep space by 25-50 percent. The collision hazards increase proportionately.[23] (see Secs 6.2 and 6.3) Although the tracked population of debris is increasing linearly (by 250-300 objects per year), not exponentially as previously predicted, it already has exceeded the natural meteoroid background (Fig. 6-4).[1-3]

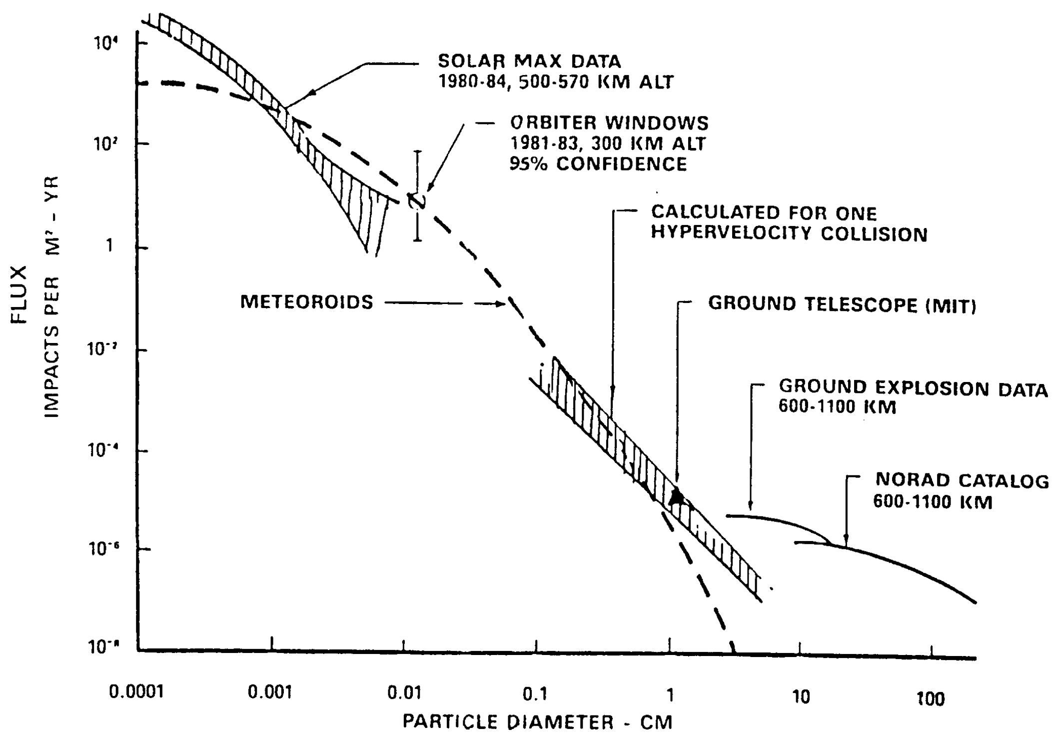


FIGURE 6-4. RECENT ORBITAL DEBRIS MEASUREMENTS COMPARED TO METEOROID FLUX (Refs. 1, 3)

Untracked smaller debris appear to dominate collision encounters. Little data on the man-made debris flux are available on debris less than 4 centimeters in size (Fig.6-1). Objects below this size cannot be detected by Space Command's deep space tracking detection systems. GEODDS (The Ground-Based Electro-Optical Deep Space Surveillance System) however, is an expanding global network of tracking sensors which is continually being upgraded to aid in monitoring space assets.[13]

Space hazards of interest to this analysis include:

- <u>Low Earth Orbit (LEO) Collisions</u> (Secs. 6.4.1 and 6.4.2):

    • Collisions between two active spacecraft in LEO between 200 km and 4000 km (120 miles and 2400 miles).
    • Collisions with both man-made and natural (meteoroids) objects in the near-Earth orbits. The hazard from man-made debris increases with time while the debris of the natural environment remains at a near constant level (Figures 6-2, 6-4).

- <u>Geosynchronous Earth Orbit (GEO) Collisions</u> (Secs. 6.4.3 to 6.4.5):

    • Collisions between active spacecraft and inactive spacecraft remaining in a geosynchronous orbit. This GEO "ring" is narrow in latitude and altitude bands, but spread over 360° in longitude (Fig.6-5).

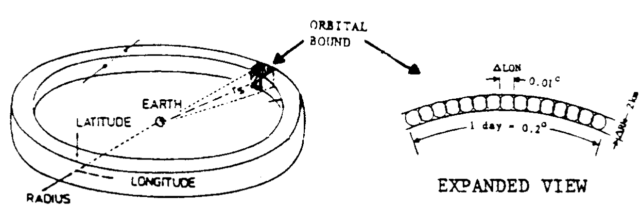


FIGURE 6-5. GEOSTATIONARY RING SHOWING SATELLITE ORBITAL BOUNDS

The collisions may result from the accumulation of inactive spacecraft in the most desirable GEO orbits for communication satellites.

- Collisions between two active spacecraft in geostationary orbit. These collisions can be prevented if collision avoidance procedures are invoked by ground control or by judicious orbital slot allocation.
- Collisions between active spacecraft and spent orbital transfer stages in GTO or other debris in GTO and GEO. The probability of collision with objects in geo-transfer orbit (GTO) is relatively small due to the short dwell and transit time of geo-transfer objects in the geosynchronous band (about 3% of their period).

When considering objects large enough to damage most spacecraft, artificial debris, whose sources are discussed in Sec. 6.3, constitute the dominant threat.[2,3] Collisions involving artificial and meteoritic debris possess these differing characteristics:

1) Collision hazards are proportional to the debris population densities, relative orbital velocities between colliding objects and the cross sectional area of the orbiting spacecraft.

2) Large debris consist primarily of artificial objects, while small debris are dominated by natural meteoroids.

3) Meteoritic debris remain at a relatively constant level, while the spatial density of man-made debris is increasing with time.

4) Artificial debris populate circular orbits with rather low relative velocities, while meteoritic debris orbits are elliptical with larger relative velocities at collision. The average velocity of meteorites relative to spacecraft is roughly twice as large as that of man-made objects, namely 14 km/s vs. 7 km/sec. However, cometary debris move in elliptical and sometimes retrograde orbits and can therefore reach 40-70 km/sec. relative impact velocities.

6.2 SPACE LAW AND SPACE DEBRIS ISSUES

6.2.1 The Regulatory Framework for Orbit Allocation and Space Debris

Major international agencies that establish and implement space law, as it applies to communication and remote sensing satellites, include:

- United Nations Committee on the Peaceful Uses of Outer

Space (COPUOS)
- International Telecommunication Union (ITU)
- International Telecommunications Satellite Organization (INTELSAT)
- International Maritime Satellite Organization (INMARSAT)

COPUOS is the foremost entity of these agencies since the major space treaties in effect today have been negotiated under its auspices. The ITU is the principal agency that deals with regulatory matters pertaining to satellite communications. It receives support from several other organizations, namely:

- The International Radio Consultative Committee (IRCC)
- The International Frequency Registration Board (FRB)
- The International Telecommunications Satellite Organization (INTELSAT)

Of these organizations, the IRCC is the most likely to be involved with the problem of satellite collisions. Specific groups have been established within the IRCC to study special subjects, primarily in the areas of space communications and interference problems. INTELSAT is dedicated to the construction, deployment and operation of commercial telecommunication satellites.

A majority of nation-states must first endorse international treaties and regulations, in order for them to become effective. The implementation of such treaties requires all member states to abide by the dictates of the majority. Therefore, any proposal pertaining to on-orbit collision risk reduction and orbital debris management would require several years for discussion, consideration and ratification in an international forum.

Presently, only communication satellites are assigned orbital and frequency windows through international agreements. Other commercial, research and military missions go through a process of orbital parameter optimization prior to mission approval to avoid collisions during their useful life. These are simply registered with the UN by the launching state. USSPACECOM can identify space object fragmentation events and infer their probable cause: for example, if orbiting satellites cross in space and time disappear and the crossover point becomes strewn with debris, a mutual collision can be inferred. It is difficult to assign liability and to determine whether a collision encounter on-orbit was accidental or intentional. The National Ranges, as well as NASA and the Satellite Surveillance Center (SSC) within USSPACECOM, usually perform COLA (COLlision Avoidance at launch) to determine safe launch windows and COMBO (COmputation of Miss Between Orbits) screening runs for proposed missions to check the proposed orbits against cataloged orbits. A "point of closest approach" (PCA) is computed. If a risk exists, orbital maneuvering capability or orbital parameter changes are provided. Hence, preplanning of missions avoids collisions with known and tracked space objects. While COLA is run routinely prior to launch, COMBO runs are complex and costly, so that orbital safety screening has been done only for select US Government missions. Smaller debris which cannot be radar tracked pose unpredictable hazards. "Rules of the road" for satellite close approaches are currently being considered to avoid international conflicts in space.[28-30]

6.2.2 Orbital Debris Issues

An assessment of collision hazards in space requires a study of collision probabilities between all objects in space including those of natural origin (i.e., meteoroids) as well as man-made objects (satellite and space debris). Orbital debris consist of: spent spacecraft, used rocket stages, separation devices, shrouds and fragments from accidental or deliberate explosions and collisions.[1-3] A major concern for future space activities is the possibility of generating a debris belt as a result of cumulative collisions between orbiting objects.[1-14] Several models, discussed below, have been developed to estimate quantitative collision hazards for spacecraft in both low earth orbit (LEO) and geostationary orbit (GEO) regimes.[15-20] Each of these models relates the collision hazard to the orbital population density and to the relative object velocity. Estimates of collision probabilities between spacecraft and debris in LEO and GEO show that, at present, this hazard is still small (1 in 1000 and 1 in 100,000 per year in orbit, respectively), but increasing rapidly (Figs. 6-2, 6-3). The threat of losing on-orbit satellites through collisions with other inactive satellites or orbiting debris is not yet critical, but is becoming increasingly serious. The more crowded regions of space which are optimal for man-rated systems (like the Space Station), larger satellites or those used for communications, remote sensing, navigation and surveillance missions are of most concern.

Proposed space debris management options under consideration include the following:[4,13,24,31]

- provide impact hardened shielding to new satellites, as well as added orbital maneuvering capability to avoid collisions;
- require that extra fuel be provided to satellites inserted into more crowded space orbits to enable their transfer into either higher and longer lived "parking" orbits, or into lower decaying "disposal" orbits at the end of their life. International cooperation and agreement is needed to define such parking and disposal orbits;
- undertake "space salvaging" operations to retrieve and

remove dead payloads from more crowded orbits. This "celestial trash can" could be ejected from the Solar System, injected into a Sun bound orbit or fitted with rockets for controlled re-entry to Earth. The latter would allow "disposal" by atmospheric burn-up, but would increase re-entry hazards (Ch. 7).

6.3 ORIGIN OF ORBITING DEBRIS

6.3.1 Hypervelocity Collisions

Hypervelocity collisions in orbit can generate a significant number of debris particles which are too small to be observed, yet sufficiently large to inflict damage to any unhardened spacecraft. Uncertainty about the population of unobserved debris particles is the most important factor limiting an accurate assessment of space collision hazards (Figures 6-3,6-4). Ground based tests of hypervelocity impacts indicate that a single high speed collision in space could produce between 10,000 and 1,000,000 pieces of debris. Table 6-1 provides estimates of the number of debris objects which could result from collisions between different size objects [7].

TABLE 6-1. FRAGMENTS GENERATED IN HYPERVELOCITY COLLISIONS[7]

Colliding Objects	Debris Generated K	G	M
K/K	100	4000	40,000
K/G	-	50	2,000
K/M	-	-	50
G/G	-	50	4,000
G/M	-	-	50
M/M	-	-	50

K: Objects larger than 1 kilogram
G: Objects in the gram to kilogram size range
M: Objects in the milligram to gram size range

Verification of the results of high speed collisions in space is hampered by the difficulty in observing the small particles. Given the present tracking capability, it is difficult to differentiate between a fragmentation caused by a hypervelocity collision or an explosion.[4] There have been no confirmed instances of satellite damage due to high speed collisions with debris in space to date.[4] The subject of collision by-products is closely tied to the generation of the so-called "debris belt" which could result from cumulative collisions. While such a catastrophe would cause severe problems for future space ventures, it is not considered a likely consequence for many years to come.

6.3.2 Explosions and Spacecraft Breakups

Explosions and breakups of spent propulsion stages and spacecraft on-orbit (either spontaneous or collisional) are a major source of space debris (Figs. 6-6, 6-7 and 6-8). More than 90 known break ups have occurred in orbit, as of January, 1986.[2,3,7,13,14,21,22] For the 39 satellites known to have fragmented in orbit, 15% of the events are propulsion related, 40% were deliberate and the rest are due to unknown causes. Explosions, both inadvertent and intentional, represent the largest single source of space debris and account for approximately 60 percent of the tracked space objects. These are almost equally divided among non-operational payloads and remaining mission related expendable objects, such as rocket stages, shrouds, etc. Debris originating in one collision or explosion event will cluster in orbital parameters (inclination, eccentricity) so that locally, the probability of impacting an orbiter is much higher (Fig. 6-8).

As of July 1982, 49 percent of the cataloged population had originated from a total of 44 break ups. In November 1986, an Ariane 3rd stage, launched nine months earlier, exploded and created a cloud of debris in polar orbit, centered at 490 mi. altitude, but spread as low as 270 mi. and as high as 840 mi. Ariane 3rd stages are known to have exploded on orbit at least 3 times before this, as indicated by SPACECOM tracking data. On orbit explosions also have been associated with second and upper stages along with casings from Proton, Ariane, Delta, Titan, Atlas and Atlas/Centaur spent stages. There have been ten Delta 2nd stage explosions in orbit prior to 1981, but none since 1982 (see below).

The increase in LEO hazard level caused by the explosions of several US ELV second stages in the early 80's (see Sec. 6-2) is less pronounced at elevations of 600 to 1200 km than in the 300 km range because the relative debris level is lower at these altitudes. It is estimated that for an explosion which produces

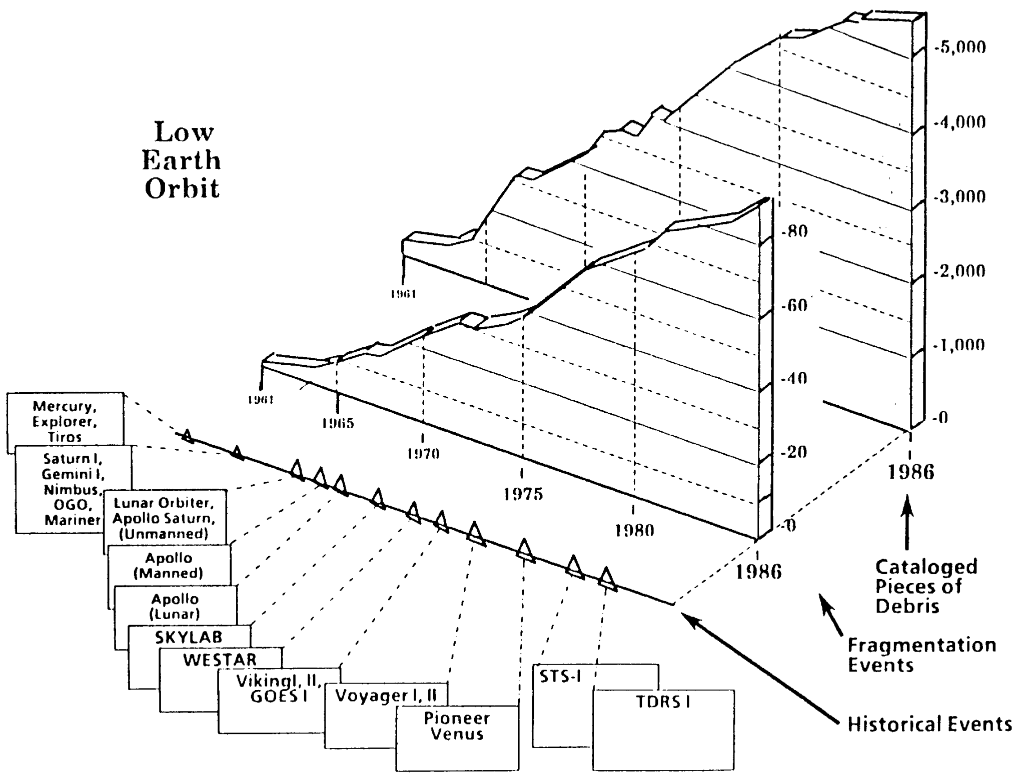


FIGURE 6-6. HISTORY OF ON-ORBIT FRAGMENTATIONS (AS OF 1 JANUARY 1986)

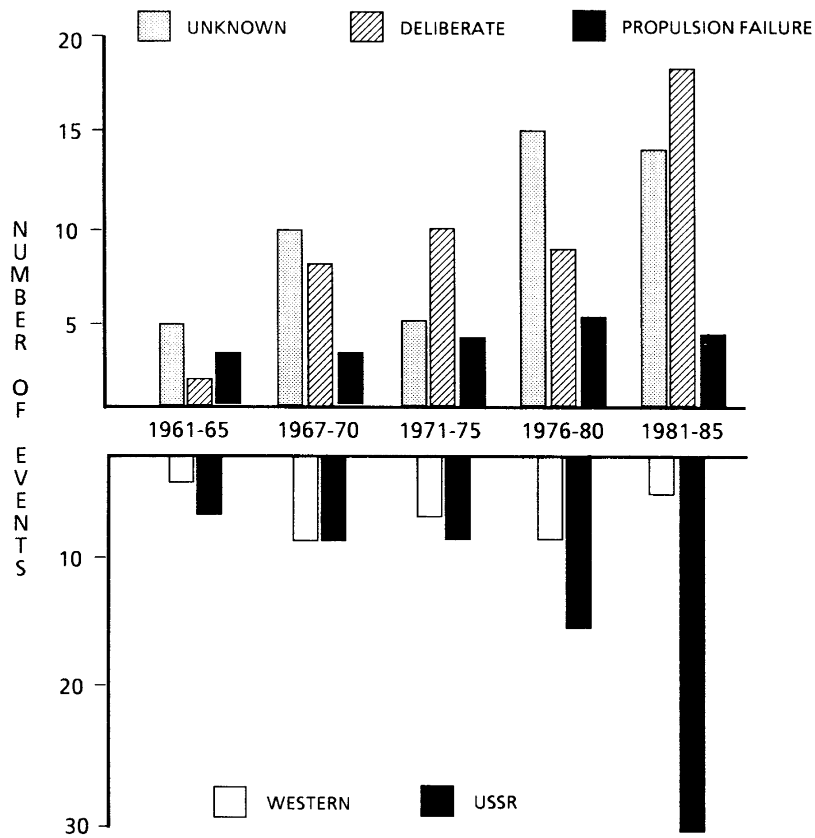


FIGURE 6-7. HISTORY OF SATELLITE BREAK UP EVENTS (REF. 2)

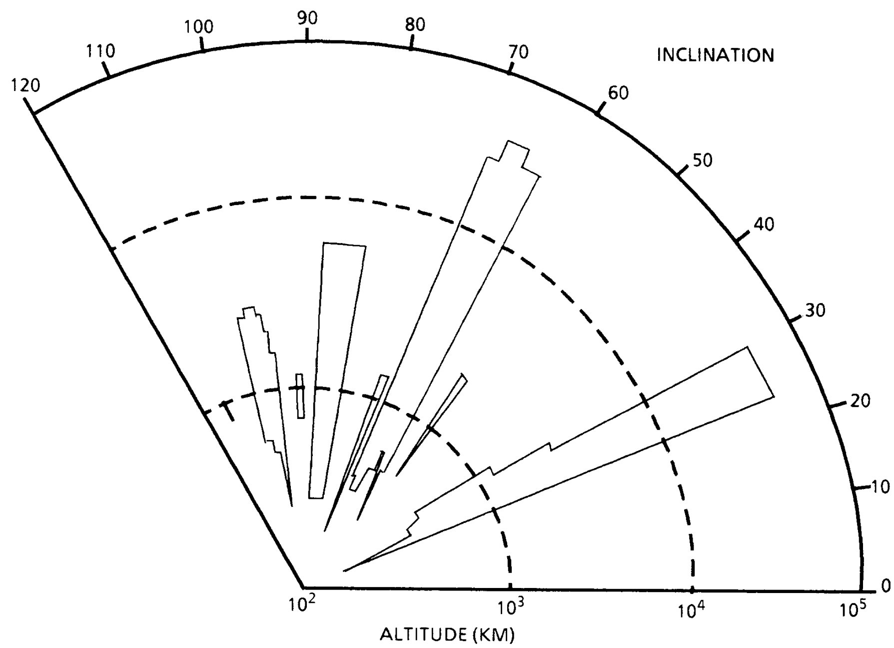


FIGURE 6-8. SATELLITE BREAK UP DEBRIS REGIONS

500 fragments, the time between collisions involving one of these fragments would be about 50,000 years.

Since 1986 steps have been taken to stop such explosions by venting all residual fuel in jettisoned 2^{nd} and 3^{rd} stages (i.e., fuel depletion burn). This residual fuel tended to explode upon thermal cycling and overpressurization due to solar heating, especially for sun-synchronous orbits. A recent change in operating procedures requires residual liquid fuel of spent second stages (and upper stages, if liquid fueled) to be vented to prevent and control on-orbit explosion generated debris. However, Ariane upper and transfer stages have exploded on-orbit as recently as 1986 and 1987 since ESA has yet to adopt a venting policy.

Ground simulated Atlas explosions, used as calibrations tests for fragmentation, produced about 1300 fragments. On September 20, 1987, the Soviet satellite Cosmos 1769 (suspected to be nuclear powered) was intentionally destroyed on-orbit producing a cloud of debris at about 210 mi. altitude and 65° orbital inclination. Reference 25 lists past satellite breakups and the number of cataloged objects generated by the breakups. Extrapolating the number of on-orbit explosions and break ups, the SPACECOM catalog could expand by up to a factor of 10 in the next 20 years.

6.3.3 Orbiting Nuclear Payloads

Special on-orbit hazards are posed by the increasing number of nuclear power sources, both active reactors and passive fuel cells.(13,24) Therefore, approval of nuclear missions is subject to more rigorous risk assessments, planning and review by an Interagency Nuclear Safety Review Panel (INSRP). There are about 50 potentially hazardous satellites in orbit today, carrying over 1.3 tons of nuclear fuel, much in the form of long life toxic isotopes. These pose both on-orbit collision and re-entry hazards (see Ch. 7). The 48 radio-thermal generators (RTG) and fuel cores orbiting today are in the most crowded LEO region at about 1000 km altitude. Both US and Soviet satellites have exploded or spawned debris in this belt. However, since 90% of the Soviet nuclear material in RORSAT satellites has been intentionally ejected into higher orbits at 900-1000 km at 65° inclination, the hazards to population due to re-entry or possible ground impact have been removed. This procedure is intended to increase the orbital lifetime to more than 1,000 years to allow sufficient time for the radioactivity to decay. The eventual retrieval and elimination of these materials is possible by sending them, for example, into escape orbits or into the Sun. Hypervelocity collisions with nuclear satellites and their fragments could endanger, contaminate and disable both manned and unmanned spacecraft with perigees well below 1000 km.

6.4 ASSESSMENT OF COLLISION HAZARDS IN ORBIT

6.4.1 Collision Hazard in LEO

Low Earth Orbits generally include the altitude range of 200 km to 4000 km. This region has the largest spatial density (Number/km^3 -see Fig.6-1) of space objects, with a maximum of 1.7×10^{-8} objects/km^3 between 800 and 850 km and 2.5×10^{-8} objects/km^3 between 950-1000 km altitude. This corresponds to a mean time between collisions of 1/1800 years for a satellite with a cross section of 100 m^2, the size of the Soviet Mir Space

Station (Fig. 6-3). Figure 6-9 shows the observed population of satellites, as modified by the debris density. This density exhibits two maxima, one near 800 km (480 miles) altitude and the other near 1400 km (840 miles). The actual debris population is likely to be considerably larger than that shown in Figures 6-6, 6-8 and 6-9. Decay of space objects, i.e., re-entry to Earth, occurs primarily from low altitude orbits and results from atmospheric drag which increases with the level of solar activity. A typical orbital lifetime at 300 km is less than one month; below 200 km, it is just a few days. These de-orbiting spacecraft will re-enter Earth's atmosphere and contribute to re-entry hazards (see Ch. 7).

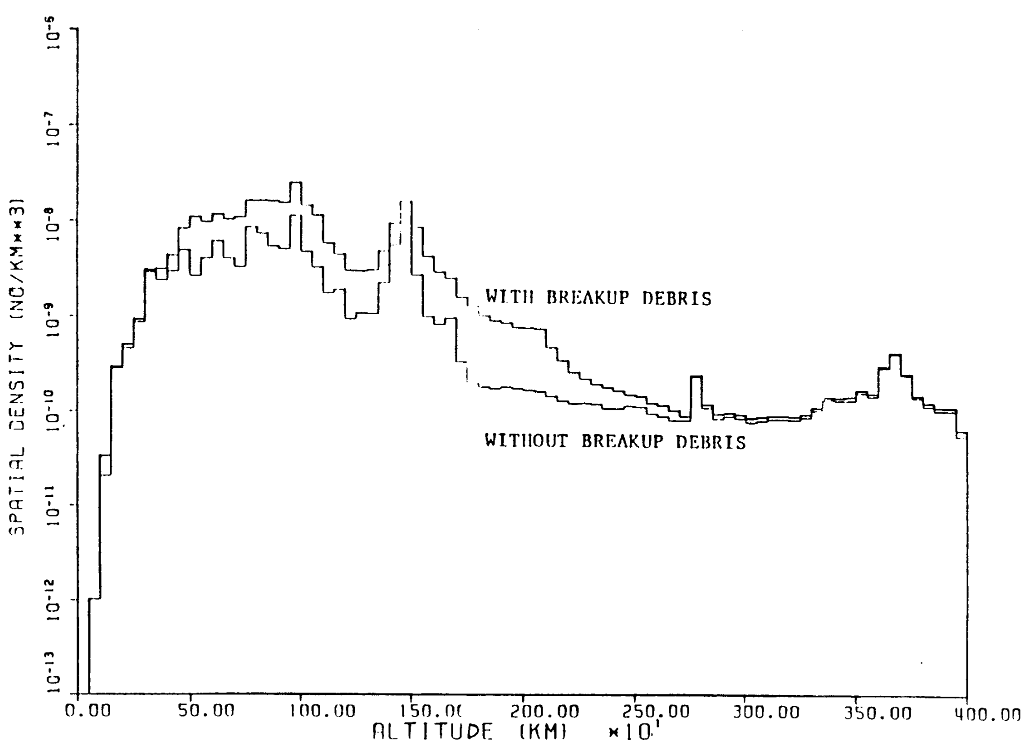


FIGURE 6-9. CONTRIBUTIONS OF BREAK UP DEBRIS TO LEO SPATIAL DENSITY

If the worldwide satellite population continues to increase at 150-180 /year (as was the case for the past 5 years)[5] and all these objects penetrated the maximum density altitude band (950-1000 km), the LEO spatial density would still not be expected to increase by a factor of 10 until between the years 2044 and 2100.

Many Earth satellites (83%) which reside in LEO decay in orbit within a few days to several years. Solar flare and sunspot activity cycles periodically "purge" these orbits (see Refs. 13,29 and Chs. 4,7).

Inactive satellites, jettisoned rocket motors and launch or break up debris in LEO could undergo hypervelocity impacts (at 10km/second) with active satellites in circular orbits and with others in elliptical orbits which traverse this altitude range.

Launch activity is an important factor contributing to space hazards through the generation of man-made debris. Table 6-2 shows the number of space launches since 1980 and the projected number of space launches anticipated in the next decade.[5,6,9] The current annual USSR space activity amounts to about 105 launches per year. The Soviet program accounts for roughly 95 % of the total, largely because the useful on-orbit life of Soviet satellites is much shorter than that of equivalent US spacecraft.

TABLE 6-2. YEARLY LEO LAUNCH ACTIVITY

	YEAR															
	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
US	13	17	17	23	17	3	0	21	24	15	11	12	15	13	14	15
USSR	89	98	101	95	92	108	108	108	111	114	115	114	114	114	114	114
Other	3	8	3	9	3	7	5	5	6	5	5	22	17	21	18	14
Total	105	123	121	127	112	118	123	134	141	134	131	148	146	148	146	143

Figure 6-2 shows the relative flux distribution of meteorites and man-made objects in LEO. The meteorite flux data were based on indirect ground based measurements, including observation of meteors burning up in the atmosphere. The man-made flux data were taken from the 1986 Satellite Catalog of tracked space debris.

6.4.2 Collision Probabilities in LEO

Collision probabilities are useful in assessing space hazards, estimating collision hazards between operational spacecraft and orbiting objects quantitatively and determining the likelihood of satellite debris collisions.

Models developed for deriving probability estimates usually use the following assumptions:

- Objects in orbit are randomly distributed and each object is assigned an effective cross section.
- The collision cross section is usually the geometric cross section of the satellite.
- Orbital planes within the debris population have random distributions in the azimuthal coordinate.

Several models based on kinetic theory and celestial mechanics provide estimates of collision hazards to operational spacecraft in LEO.[11,16,20] The impact probability, per orbit or per crossing a certain orbital torus, must be multiplied by the on-orbit satellite lifetime (or the mission duration) and the cross section of the object to estimate its overall collision risk.

Probability derivations are simplified if the object density is assumed to have only an altitude dependence and all other dependencies are replaced by averages. While the latter removes the possibility of including angular orbital dependencies in the solution, it nevertheless provides a reasonably accurate estimate of the collision hazard.

One procedure used to determine the altitude dependent object distribution is to define an Earth centered spherical grid, consisting of surfaces of constant radius spaced every 50 km from 150 to 4000 km in altitude, and surfaces of constant polar angle (latitude) spaced every 5 degrees.[8] The object density within the above defined space cells is computed based on the percentage of time an object spends in the 'spherical cell.' Figure 6-2 is typical of the type of density distribution which results from this model. The mean rate of collision probability, P, is defined as,

$$P=\int_{0}^{t0} C(r,t)\,dt$$

where C(r,t) is the collision frequency equal to,

$$C(r,t) = \sigma_{eff} \cdot \rho(r,t) \cdot v(r,t)$$

Where:
- ρ = object density
- σ_{eff} = effective cross section
- v = mean speed of object relative to debris
- r = object distance from Earth's center
- t = the elapsed time.

Applying this to the example of the Shuttle Orbiter at 300 km altitude, with a debris distribution similar to that shown in Figure 6-2, gives a predicted time between collisions approximately equal to 25,000 years(8). These models estimate the collision probability for a Shuttle Orbiter at 150-300 km altitude to be roughly 1 in 25,000 years. The chance of an orbiter colliding with debris in LEO, over its lifetime, is about 10^{-3} at present and may exceed 10^{-2} by the year 2000. The larger collision risk for spacecraft which operate in the 600 to 1200 km range of maximum debris population, is offset by the smaller cross sections of operational spacecraft at these altitudes. This result assumes a typical Shuttle cross sectional area of 250 m^2 and a relative impact velocity of 7 km/s. Man-made debris of size 4 cm and smaller do not present a significant hazard to LEO spacecraft with dimensions comparable to that of the Shuttle. A future Space Station 100 m across in LEO at a 500-550 km altitude, would have a mean life to collision of 170 years without debris, but of only 41 years given the present debris strewn near-Earth environment.

Inclusion of the latitude dependence in the probability estimate yields similar results. Table 6-3 gives the predicted time between collision as a function of orbital inclination with the same LEO debris population used previously (see also Fig. 6-8). Greater debris hazards are anticipated for spacecraft operating at higher altitudes, particularly in the range from 600 to 1200 km where debris density is greatest (Fig.6-2). Table 6-4 gives the estimated time between collisions for a small spacecraft, of 5 m^2 collision cross section, with man-made debris assuming a relative speed of 7 km/s. There is evidence that some spacecraft in LEO have already collided with either natural or artificial orbiting debris.

TABLE 6-3. COLLISION TIMES FOR A SHUTTLE ORBITER WITH LEO DEBRIS[8]

Shuttle Orbit Inclination Angle (deg)	Time between Collisions (years)
28.5	2.7×10^4
56	2.0×10^4
82	1.6×10^4
90	1.5×10^4
98	1.4×10^4

TABLE 6-4. TIME BETWEEN ON-ORBIT COLLISIONS VERSUS LEO ALTITUDE[8]

Orbit Altitude (km)	Collision Time (years)
648	1.8×10^5
741	5.3×10^5
833	4.8×10^5
926	6.1×10^5
1019	7.5×10^5
1111	1.5×10^5
1204	3.5×10^5

6.4.3 Collision Hazard in Geosynchronous Orbit (GEO)

Conceptually, the geosynchronous orbits can be visualized as a spherical shell several kilometers thick located at an altitude approximately 36,000 km above the Earth. Spacecraft in geosynchronous orbit move with the rotating Earth at arbitrary angles of inclination with respect to the equator. The geostationary orbit represents a particular subclass of the geosynchronous orbits in which objects move synchronously with the rotating Earth, but with positions fixed relative to its rotating coordinate system. The geostationary ring denotes a particular region in geosynchronous space, of approximately several hundred kilometers in width, encompassing these orbits.

The main characteristics of geosynchronous orbits are:

- Orbital period is equal to one sidereal day (1436.2 minutes or 24 hours).
- An infinite variety of orbits exist each with the same average altitude as a geostationary orbit.
- Objects in orbit cross the equator twice each day with average velocity of 3075 m/s.
- The equatorial crossing point of the object drifts cyclically along the equator due to unbalanced Earth gravity.
- Objects remain permanently in orbit (as in the geostationary ring).

The main characteristics of geostationary orbits are:

- Altitude above Earth is 35,787 km (19323 nautical miles) ± 50 km.
- Orbit is exactly circular over the Earth's equator (± 1^0 latitude).
- Orbital period is 1436.2 minutes or roughly 24 hours.
- Objects in orbit have an orbital velocity of 3075 m/s.
- Objects remain permanently in orbit, i.e., the decay rate is very slow and secular, about 1 kilometer per thousand years.
- Objects in orbit are subject to weak luni-solar and Earth gravitational perturbations which result in slow drift in east-west and north- south directions about the two geo-stable points at 75.3°E and 104.7°W longitude. This results in eventual clustering of inactive satellites in these regions.

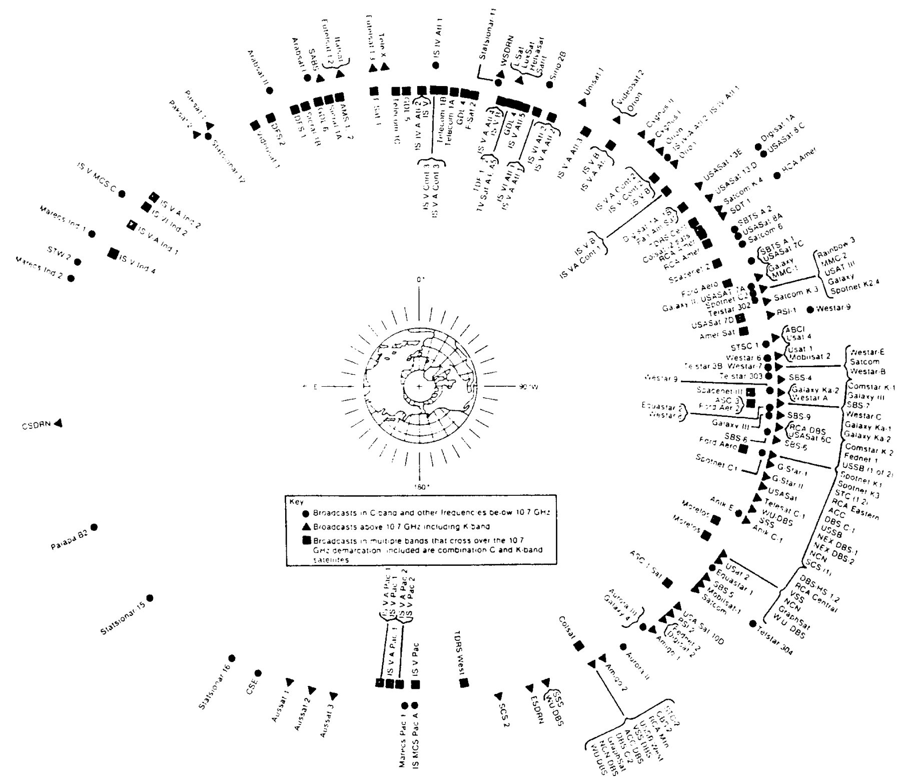
Semi-geosynchronous orbits (i.e., at half the GEO altitude with 12 hour periods) are also used for communication satellites. Such highly elliptical "molnyia" (lightning) orbits are favored by the Soviets because the satellite spends most of its time above the Soviet Union moving slowly near apogee, but crosses rapidly over antipodal regions near perigee. Such orbits degrade more rapidly due to atmospheric friction near perigee.

The largest concentration of operational spacecraft lies in the geostationary belt and currently numbers over a hundred spacecraft. Extinct satellites also continue to orbit in the crowded GEO orbits, presenting a mounting collision damage hazard to new communication satellites (Fig. 6-3). Some nations and organizations have begun to move inactive satellites out of GEO to prevent cluttering of the GEO ring. However, according to Ref. 3 (Ch. 4), the removal of inactive satellites from GEO stations at the end of their useful life is not yet a general practice. The policy of using disposal orbits for defunct satellites has recognized shortcomings which may introduce new hazards to active payloads (e.g., the potential for misfire or explosion, eventual migration of "removed" payloads to GEO due to luni-solar perturbations and solar wind pressure, added cost for stationkeeping and orbital maneuvering propellants and decreasing reliability with life on- orbit.)

The peak spatial density (number per km^3) of satellites at GEO altitudes (35,750 to 35,800 km) is due to about 543 satellites, of which only about 150 are geostationary. The others are in either geosynchronous, or semi-geosynchronous highly elliptical "molnyia" orbits. The corresponding spatial density value is 7.55×10^{-10} objects, still 2-3 orders of magnitude below that in LEO.

The current geosynchronous population, as tracked by USSPACECOM, consists of about 116 active communication satellites plus at least as many uncontrolled objects drifting through the geosynchronous corridor. The latter includes inactive satellites and debris which drift around the Earth or oscillate about the two geo-potential stable points. USSPACECOM can track an object of the size of a soccer ball in GEO and of about ò 10 cm. in LEO (Figs. 6-1, 6-4). Figure 6-10 shows the relative positions of the commercial communication satellites in GEO. The number of active GEO satellites over the past few years and the estimated number of GEO launches in the coming decade is shown in Fig. 6-10 and Table 6-5.[5,6]

Thus, collisions in GEO are restricted to object encounters at a fixed altitude of approximately 36,000 km, actually an equatorial torus of 1^0 in latitude and 35, 785 ±50 km altitude above the Earth's equator. Such collisions can involve both man-made objects and natural objects (meteoroids).



NOTE:
1. IS refers to INTELSAT satellites.
2. The following are USSR satellite series: CSDRN, Ekran, EŞDRN, Gorizont, Loutch, Potok, Prognoz, Raduga, Statsionar, Volna, WSDRN.
3. Multiple orbits are for legibility only. All geosynchronous satellites orbit at approximately 22,300 miles above the earth.

FIGURE 6-10. PLANNED LOCATIONS OF COMMERCIAL COMMUNICATIONS SATELLITES IN GEO AS OF 1984. (REF. 6)

TABLE 6-5. GEO LAUNCH ACTIVITY

	Year										
	85	86	87	88	89	90	91	92	93	94	95
US	16	14	13	15	16	14	17	14	19	20	27
USSR	5	5	5	5	5	7	7	7	7	7	7
Other	6	9	7	4	3	8	3	1	6	12	9
Total	27	28	25	24	24	29	27	22	32	39	43

Estimated collision probabilities with debris in GEO are of the order of 10^{-5} at present, but could reach 2×10^{-3} over the life of the satellite, (i.e. 1 in 500) by the year 2000. Therefore, at current GEO population levels, collision hazards do not appear to be a major problem.[1-4,9,17] The collision hazards in GEO tend to be lower than in LEO for the following reasons:

(1) the lower spatial density of GEO satellites, although new communication satellites are increasingly crowding GEO orbits(Fig. 6-2);
(2) the relative velocity difference between objects orbiting in GEO is less than for LEO;
(3) most active spacecraft in GEO require accurate position control and station-keeping above their Earth subpoint, thereby reducing the likelihood of mutual collisions.

These considerations, however, are offset by the limited orbital slots available in GEO and the steady increase in the number of GEO satellites launched each year (Fig.6-10). Also, meteoroids cross the GEO belt with high relative velocities, so their background collision hazard remains at a level comparable with that of LEO. An unknown factor is the amount of unmonitored debris in GEO, because objects at such high altitude are more difficult to detect and monitor with radar or optical telescopes.

A number of articles discuss the collision probabilities of satellites in GEO.[10-20] In general, the collision probability is a complicated function of orbital parameters, relative position, velocity, projected areas of the spacecraft and time. The collision probability, P, of satellite collisions assuming a uniform distribution of space objects is,

$$P = A \cdot \rho \cdot v \cdot t$$

where:
- ρ= object density
- A= projected area of the satellite
- v= relative velocity of the target satellite
- t= time interval associated with the (periodic) satellite motion

Takahashi[15] and Chobotov[11,16] have developed models for estimating collision probabilities for GEO satellites. Both models use the above relation as the basis for derivation of collision probabilities. Takahashi assumes the target satellite stays within fixed longitude/latitude bounds by appropriate station keeping. The satellite motion includes a small diurnal oscillations superimposed on a steady longitudinal drift. Maneuver corrections are applied every 15 days to maintain the satellite within the fixed longitudinal bound.

The right hand side of Figure 6-5 illustrates the diurnal oscillation/drift motions assumed by Takahashi. The satellite orbital bounds were assumed to be 0.01^o, 0.05^o, and 2 km for the longitude, latitude and altitude respectively.

If the orbital bounds for the diurnal motion are expressed in terms of increments in longitude Δ LON, latitude Δ LAT and altitude Δ ALT, the collision probability in three dimensions per orbit takes the form:

$$P = N \cdot (2\prod R) \cdot L^2 \cdot (\Delta LON \cdot \Delta LAT \cdot \Delta ALT) \cdot (\Delta LON + (2/\prod) \cdot \Delta LAT + \Delta ALT/R)$$

where L is the satellite diameter. The incremental bounds Δ LON, Δ LAT and Δ ALT are set by the magnitude of the diurnal motions along the longitude, latitude, and radial coordinates which are assumed to be equal to 0.01^o, 0.05^o and 2000 meters respectively. If an additional factor of 1/10 is introduced to account for the fact that collisions are only possible one out of every ten diurnal periods due to the longitudinal drift, then with these substitutions the above equation takes the form:

$$P = 9.51 \times 10^{-9} \times L^2 \text{ per half day}$$

This yields a satellite collision probability of $7 \times 10^{-6} \times L^2$ per year. For satellites having dimensions typical for those used in space communications, i.e., L=2 meters, the probability of collisions in the geostationary orbit is extremely small. This changes when large space structures are considered, such as proposed satellite "farms," solar power satellites or orbiting space platforms. For an orbiting satellite of dimensions approaching 125 meters, the annual likelihood of a collision is about one in ten. For a hypothetical satellite "farm" of dimensions of 1000 meters, the expected frequency of collision increases to approximately once every 52 days.

The Chobotov approach considers the collision probability between geostationary satellites in circular orbits (in the equatorial plane) and geosynchronous satellites moving in an orbital plane with small inclination angle i and orbit eccentricity e. The satellite density, ρ, is proportional to the relative dwell time the satellite spends within a spatial volume defined by the following "bounds":

Longitude bound = $2 \Pi R$, Latitude bound = $2 R \sin i$,
Altitude bound = $2 R e$,

where: R is the distance of satellite from Earth's center.

For a geostationary satellite of radius R_s, the probability of collision, P, with another satellite in one revolution or a 24 hour period is on the order of $P = 2.83 \times 10^{-13} R_s 2$ per day.

For a population of over 200 satellites, assuming one satellite every 2^o longitude, each with radius of 50 meters, the probability is 2.2×10^{-9} per day. Hence, the probability of a collision between a satellite in a circular geostationary orbit with other satellites in low inclination orbits is extremely small.

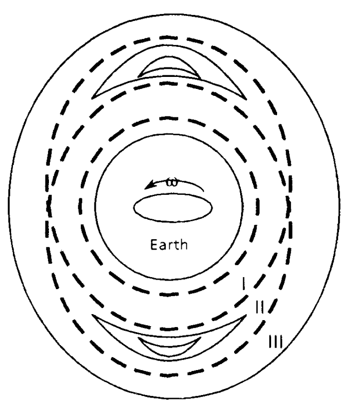
This probability of a collision between a spacecraft and spent GEO transfer stages is approximately two orders of magnitude less than that between two active GEO spacecraft, because of to the relatively small percent of the time (approximately 3%) that an object in an elliptical GEO transfer orbit spends at geosynchronous altitudes. The semi-geosynchronous ("molnyia") orbits favored for Soviet communication satellites are highly elliptical with low perigees and high relative near-Earth velocities.

To summarize, the low typical spatial densities in GEO of 2.5 - 7.5×10^{-10} objects/km^3, due to the roughly 550 objects which orbit in the 35, 750 + 50 km bin, combined with lower relative velocities in GEO and with typical station keeping capabilities, the probability of on-orbit collision is negligible at present(24).

6.4.4 Gravitational Drift Forces in GEO

Secular gravitational forces play an important role in altering the orbital characteristics of geosynchronous satellites. Depending on the point of origin of these forces, their effect on the orbit can be markedly different. These forces include the gravitational forces associated with the Earth's oblateness and the gravitational attraction of the Moon and Sun.[26]

The oblateness of the Earth (bulge in its in the equatorial plane) produces longitudinal drift forces in the east-west direction associated with the two geo-stable points located near 104.7°W and 75.3°E longitude. Without station-keeping capability, these forces cause GEO satellites to move in elliptic orbits in the longitudinal (and radial) direction with an oscillation period of about 820 days. Figure 6-11 shows a pictorial view of these drift oscillations.[27] The amplitude of excursion about these geo-stable points depends on the initial orbital departure from the geo-stable points, with the amplitude being zero for orbital paths that happen to cross the equator at the geo-stable points.



Region I: Orbital periods shorter than 24 hours.
Region II: 24 hour orbits.
Region III: Orbital periods longer than 24 hours.

FIGURE 6-11. SATELLITE ORBITS RELATIVE TO EARTH

A second type of gravitational force is associated with the gravitational attraction of the Moon and Sun, which generate 'drift' forces along the north-south direction. The latter forces act to alter the inclination of the geosynchronous orbit causing an initial change in orbital inclination of about 0.86^{o} per year. A maximum inclination of 15^{o} is achieved in about 27 years at which point the inclination proceeds to decrease to zero in another 27 years. Superimposed on the above cyclical motions are small amplitude oscillations in the longitudinal and radial directions. These diurnal oscillations are characterized by a cyclic period of one (sidereal) day and have vastly smaller amplitudes (a factor of 10^6 and 10^3, respectively) compared to the longitudinal and radial motions described previously.

6.4.5 Collision Encounters in Geosynchronous Orbits

While slot allocation of GEO satellites generally attempts to maintain a minimum separation of two degrees longitude, in practice several satellites may share a common longitudinal location. This has led to procedures developed by the United States Air Force Satellite Control Facility (USAFSCF), recently designated the Consolidated Space Test Center (CSTC), to monitor all close approaches between primary communication satellites and other trackable objects coming within 300 km of these satellites. Predictions are made for all close approaches every seven days and appropriate user agencies are notified when the separation distance approaches 50 km. Collision avoidance maneuvers are considered at 5-8 km separation and are implemented if near simultaneous tracking of both space objects one to two days before encounter (closest approach) verifies the predicted positions of the satellites as accurate.

Typical data on geosynchronous orbit encounters over a 6 month period show that for 21 satellites examined there were 120 predicted encounters within the 50 km minimum miss distance.[(15-17)] Of these, several were in the 1-5 km range and required collision avoidance actions. The mean distance of closest approach was 21 km with a standard deviation of 13 km. Collision probabilities for these satellites were found to be up to two orders of magnitude greater than would be expected based on average density of objects in the geosynchronous corridor.

A total of six fragmentation incidents have occurred in the geosynchronous corridor, which have been suggested by some to be the possible result of actual collisions. In at least one of these, the satellite broke up into smaller debris components.

The question arises as to the potential liability of satellite owners and users for collision damage resulting when their spacecraft becomes inactive, remains in GEO, and collides with an active satellite. The accumulation of significant numbers of inactive satellites in GEO poses increasing collision hazards for active satellites. Takahashi estimated this collision probability using the same method previously applied (see Sec. 6.4.3) in the case of collisions between active satellites. Inactive satellites are assumed to have motion perturbations dictated by the Earth and by luni-solar gravitational/drift forces. Diurnal oscillations caused by the Earth's gravitational perturbations are superimposed on long-term (2-3 years) orbit evolution about one of two geo-stable points located at 75°E and 105°W longitude. Figure 6-12 shows a sketch of the long-term orbital evolution relative to Earth fixed coordinates. An additional secular motion excursion occurs in the north-south direction, causing a latitude variation of ±14.7° in a 54-year period.

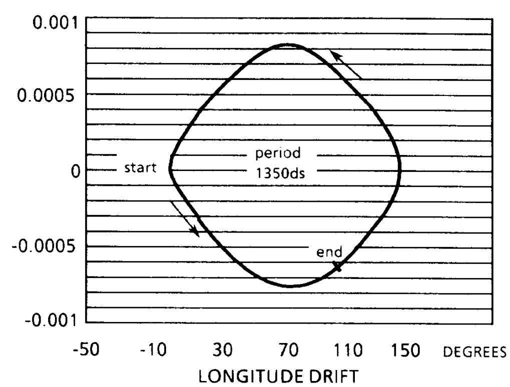


FIGURE 6-12. INACTIVE SATELLITE TRAJECTORY

The collision probability is estimated by determining the likelihood of collision in one sidereal day of a satellite confined within geosynchronous bounds of 0.1^o longitude, 7.35^o latitude and a 30 km altitude range. The effect of the secular orbital oscillations is to reduce the collision probability by a factor of 1/900. The estimated collision probability between an active and 'N' abandoned satellites of dimension 'L' then becomes:

$$P = 5.185 \times 10^{-13} \times N \times L^2 \text{ per half day.}$$

This gives a probability of 6.0×10^{-6} per year for a collision between an active satellite and an assumed total of 1000 abandoned satellites, each 4 meters diameter.

If the active satellite is assumed to be a large space platform of 125 meters across, the probability of collision with an estimated 1000 inactive satellites in one year increases to:

$$P = 730 \times 5.185 \times 10^{-13} \times 125^2 \times 1000 = 0.00591 \text{ per year}$$

Similarly, if a large solar power satellite with hypothetical dimensions of 1000 meters will be stationed in GEO, the collision probability in 1 year will become a sizeable 0.38 per year.

Hence, large GEO satellite clusters or platforms will have a high probability for collisions, if the number of abandoned communication satellites is allowed to approach 1000.

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